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E.1 Executive Summary

Background and Objectives
In late 1993, the RTCA was requested to review the characteristics of GPS and GLONASS aeronautical navigation receivers, identify potential sources of harmful interference, and recommend interference mitigation methods. This activity was assigned to Working Group 6 (WG/6) of Special Committee 159 (SC-159).

In the Fall of 1994, a Memorandum of Understanding between the FCC, NTIA and FAA requested that, under the auspices of the RTCA, the aviation and mobile satellite service (MSS) interests attempt to reach a consensus on: a) standards for out-of-band emissions from MSS mobile earth stations (MESs) for protection of Global Navigation Satellite Service (GNSS) receivers, and b) GPS/GLONASS receiver susceptibility standards. Since consensus was not achieved in all matters, this Appendix summarizes the perspective of the MSS participants in WG/6.

RTCA normally addresses the technical characteristics of avionics systems for the development of aviation standards. The MSS community has restricted their perspective comments to technical matters and has not attempted to address regulatory or other concerns.

The Central Issues
The differences between the aviation and MSS communities center on the acceptable level of the unwanted MSS emissions from MESs in the GNSS band (1565-1605 MHz) and the susceptibility of GPS/GLONASS receivers to such emissions. There appears to be agreement in both the aviation and the MSS communities that the proposed MSS emission levels are acceptably low for the use of GNSS receivers during nearly all phases of flight, including oceanic, en route, terminal area and non-precision approach operations. The aviation community does not agree that the GLONASS frequencies are adequately protected for use with hybrid GPS/GLONASS/WAAS receivers in Category I approach operations.

The FAA and the rest of the aviation community maintain that an MES wide band EIRP level of -70 dBW/MHz across the entire band of 1565-1610 MHz, and a similar narrow band limit of -80 dBW, is necessary to protect GPS/GLONASS/WAAS receivers in all phases of flight, including Cat I approaches. The MSS community believes these levels are not necessary, are extremely difficult to attain in the GLONASS band (1597-1605 MHz) and are not related to aviation safety. These unrealistic levels will place unnecessary, difficult, and in some cases impossible, technical and economic burdens on the MSS community. This concern relates almost entirely to the GLONASS band and the use of future hybrid GPS/GLONASS/WAAS receivers.

MSS Community View
The MSS community maintains that, although unnecessary, it can and will meet the stringent limits in the GPS/WAAS band (1573-1577 MHz). This can be accomplished by the MSS community at acceptable cost, even though the proposed levels are far more severe than required for safety considerations. Because of the close proximity of the GLONASS and MSS bands, MSS systems operating in the 1610-1626.5 MHz band cannot now meet, and are unlikely to ever meet, the excessive emission limits proposed by the aviation community for the GLONASS band.

In the 1597-1605 MHz band of GLONASS, the best that can practicably be achieved with present technology is a wide band EIRP limit of -54 dBW/MHz and a narrow-band limit of -64 dBW. These levels provide excellent protection to aviation users of GPS/GLONASS/WAAS hybrid receivers[1] and support more than acceptable performance margins using the standard methods for determining safety employed by the U.S. government and the aviation community.

Consequences of Arbitrary Emission Requirements
Any attempt to establish arbitrary and unnecessary emission levels in the 1597-1605 MHz band, such as those proposed by the aviation community, will result in such severe penalties to the cost, size, weight and power of MSS user terminals that the affected systems may not achieve the market penetration necessary for economic viability. This costly penalty appears unwarranted since safety considerations are met fully by the emission levels recommended by the MSS participants.

MSS Community Position on MES Emission Limits
The aviation and MSS communities could not reach consensus on the protection level to be afforded the 1597-1605 MHz band for GPS/GLONASS/WAAS-based precision approach operations given the achievable MES emission limits. The aviation community maintains that the levels proposed by the MSS community (-54 dBW/MHz for wide band emissions and -64 dBW for narrow band emissions in the band 1597-1605 MHz) are too high.

The MSS community maintains that these levels are adequate when used with the planned hybrid GPS/WAAS/GLONASS navigation sensors. These susceptibility limits appear needed in any case to protect operations in the 1597-1605 MHz band from current interfering emissions from various other sources. Also, it has been shown that in the presence of the out-of-band levels proposed by the MSS participants, these hybrid sensors provide accuracy, availability, integrity and continuity consistent with the FAA Required Navigation Performance (RNP) standards for all categories of flight including Category I approaches.

It should be noted that the narrowband (4 kHz bandwidth) emissions limits at 1605 MHz for existing licensed Inmarsat MES's are 21 dB higher than the aviation community's proposed narrowband mask. And normalized 1 MHz bandwidth broadband limits are 35 dB higher than the aviation community's proposed broadband mask. There are tens of thousands of Inmarsat MES's operating today on ocean vessels throughout the world, and by international law such MES's are allowed to transmit while the vessels are in harbors, bays, and coastal waterways near existing coastal international and regional airports. Little test data is available, but at the June 1996 meeting of SC-159 WG-6, representatives from Comsat reported that actual emissions from most Inmarsat MES's are significantly below their allowed emissions limits. Most Inmarsat MES's reportedly either meet or can be made to meet the proposed MSS community emissions mask, but meeting the aviation mask without substantial redesign is not feasible.

The MSS community bases its conclusions on the adequacy of the proposed MSS emission mask principally on the following three factors:

1. **Use of current technology in receiver design and architecture** can substantially enhance GNSS receiving systems at negligible to moderate cost and at low risk. Procedural clarification of operational conditions and reasonable specifications for aircraft GPS/GLONASS/WAAS receivers also appears appropriate.[2] Some candidate factors include:

[1] Although the GPS/WAAS MOPS (RTCA/DO-229) includes a susceptibility standard for receivers at the GPS L1 frequency, there is no existing susceptibility standard for GPS/GLONASS/WAAS receivers.

[2] The use of current technology in the GLONASS augmentation of GPS/WAAS receivers can be readily incorporated into the Minimum Operational Performance Standard (MOPS) now being developed by SC-159 and in the Standards and Recommended Practices (SARPs) being developed in the ICAO GNSS Panel.

a. Recognizing that in the U.S., (and probably internationally) GLONASS will be used only as an augmentation to GPS/WAAS navigation[3], **an elevation mask for GLONASS signals of 15 degrees when used for Cat I approach is appropriate.**[4] This provides access to the best GLONASS signals for GLONASS/GPS/WAAS Cat I operations, avoids the aircraft antenna gain degradation at low elevation angles and meets all GNSS requirements for availability, accuracy, and continuity, including those of Cat I.

b. **Incorporate into new GNSS receivers (and their MOPS) performance characteristics consistent with today's commercially available low to moderate cost GPS technology**, e.g., improved (reduced) levels of receiver thermal noise and implementation losses.

c. **Recognize antenna performance that is routinely provided by today's antenna technology.** In particular, require that all installed GNSS antennas using GLONASS signals for precision approaches have a maximum gain of -12 dBic in the downward direction (i.e., under the aircraft at elevation angles of -60 to -90 degrees).

d. **Use a realistic distance for the aircraft to MES separation** that is consistent with actual Cat I landing conditions, such as 150 feet. The value used by the aviation community (100 feet) has been arbitrarily reduced from the 200 foot (or greater) decision height by a very conservative interpretation of obstacle clearance dimensions which appears inappropriate. A value of 150 feet is compatible with virtually all Cat I rated approaches.

2. As an aircraft flies a Cat I approach using a hybrid GPS/GLONASS/WAAS receiver, the effects of MSS out of band interference on the GLONASS signals should be treated as a short-lived transient (of less than one second). This may, in certain unusual circumstances, cause the aircraft to "miss" the approach (at the 200 foot decision height) and "go around" for a second approach. Evaluation of the transient effect is appropriate. Analysis of this transient is more reasonable than assuming, as the aviation community proposes, that the effect of the MSS interference is unlimited in time. Proper treatment of interference as a transient leads to the following:

a. **An appropriate measure of the performance of a GNSS receiver under transient conditions is needed** to allow assessment of the receiver's capabilities to meet aviation's required navigation performance (RNP) standards. This is provided by the "carrier cycle slip" or the "carrier loss of lock" performance parameters. Although a cycle slip may not effect GNSS receiver performance at all times, there is a probability that it can lead to a loss of navigation continuity arising from a loss of (carrier) lock. Cycle slip performance provides a conservative metric for assessing the receiver's ability to satisfy RNP.

b. **Since a cycle slip is a probabilistic event, it can be treated as such in determining if RNP probability standards are met.** This allows a direct analysis of receiver performance in a manner consistent with classically developed probabilistic risk assessments. The MSS community has performed this analysis (see Section 6 of this Appendix) and has found that with low cost and low risk use of current technology in GNSS receivers, and with

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[3] At the 1995 ICAO COM/OPS meeting, the Russian Federation announced that it would employ hybrid GPS/GLONASS receivers for civil aviation.

[4] The following alternative may be acceptable, although it requires further study. A lower mask can be used (e.g., 5 degrees) if the receiver's signal quality and aircraft altitude solution obtained using any set of satellite signals is at least as good as similar data using the satellites above a 15 degree elevation mask. This involves the determination of satellite signal quality (C/N_0) and geometric performance (GDOP) but it takes advantage of both high power GLONASS satellites at low elevation angles and any desirable gain attributes of the aircraft antenna.

conservative assumptions on the link budgets, future GNSS receivers can readily satisfy RNP requirements as elaborated upon below.

3. Currently, navigation system risk levels are established for aviation systems by the FAA, ICAO and others. The present navigation system RNP risk allowance for lack of continuity, caused by RFI and primarily affecting the GNSS receiver, is for one alarm (possibly resulting in a missed approach) in 100,000 approaches (a probability of 10^{-5}). **The RNP is met if MSS-caused RFI alarms occur less frequently than this standard.** As described later, the probability for an MSS alarm is less than 10^{-13}, or one ten millionth of the value of the RNP standard.

Risk Assessment

The MSS community has carefully analyzed the aviation risk considering the above three factors. The use of probabilistic analysis, including the type used with RNP, is the appropriate and internationally accepted way to assess the risk to navigation performance such as that associated with RFI. This approach has been challenged by some so a few comments appear appropriate.

A GNSS receiver's impact on navigation performance requires a probabilistic assessment for many reasons. The receiver is affected by a number of independent operating subsystems and the effects of these need to be evaluated. This is analogous to the probabilistic analysis used in the assessment of an aircraft hydraulic system which may have two or three parallel and independent subsystems. Dual-redundant and triply-redundant systems are used on commercial transport aircraft today because the probability is acceptably low that all subsystems will fail at once. Simultaneous failure could result in an unacceptably high probability for loss of the aircraft.

A reference of interest relating to the importance of probability theory in aviation is the following, excerpted to indicate its relevance to the particular concern being addressed:

> "... the only satisfactory description of uncertainty is probability. This claim is generally accepted in the statistics community. Given an uncertain event A, then P(A) is the probability of occurrence of A. P(A) can be thought of as a measurement, like a measurement of aircraft position, except that in this case it measures chance, not position. ...In other words, not considering a probabilistic approach could lead to standards based upon worst-case analysis, which could be economically inefficient or (what may be less desirable) inconsistent for different phases of flight. ...Aircraft approval authorization considers operational, engineering judgment, and historical data, as well as specific risk assessments." (Reference: R. J. Kelly and J. M. Davis, "Required Navigation Performance (RNP) for Precision Landing with GNSS Application," Navigation, Journal of the Institute of Navigation, Vol. 41, No. 1, Spring 1994.)"

Probability analyses have played an important part in evaluating the safety of flight for aircraft systems involving many independent parameters. These techniques have been used extensively by the FAA, ICAO and other aviation authorities for many years, and the methodology is well known. With this heritage, it appears reasonable and prudent to apply similar probabilistic methods to the assessment of RFI as it affects the GNSS navigation performance. The only significant difference relating to the effect of RFI on a GNSS receiver is that, at worst, the RFI may cause a missed-approach as the aircraft descends to its Cat I DH altitude of about 200 feet.

Table E1-1 is a listing of most of the numerous independent, low-probability events which must occur simultaneously for MSS induced RFI to result in a loss of navigation for a GNSS receiver.

Table E1-1
Independent Events Required for RFI to Induce a Loss of Navigation During a Cat I Approach

- The GNSS constellation becomes substantially degraded (i.e. constellation geometry becomes poor) during the time interval in which a GPS/GLONASS/WAAS equipped aircraft is making a Cat I approach. This degraded condition relates to the performance of the combined GPS/GLONASS/WAAS constellation which normally contains over fifty satellites(24 GPS + 24 GLONASS + 3 WAAS).
- A substantial number of GNSS satellites which are simultaneously in view of GNSS users degrade to the point where their signal levels become close to the minimum specified EIRP value for the satellites.
- These low-power satellites are also at the lowest elevation angle allowed for use (5 degrees) during the interval of a Cat I approach by a GPS/GLONASS/WAAS equipped aircraft.
- The GPS/GLONASS/WAAS equipped aircraft GNSS receiver antenna gain toward the low-power satellites is at the antenna's minimum specified gain.
- The GNSS receiver antenna gain toward the MSS terminal is at an unusually high gain value.
- The aircraft is at the lowest part of its 95% containment tunnel, i.e., when arriving at its decision height (DH).
- The maximum-height obstacle in the area is located directly under the decision height part of the aircraft's flight path.
- The MSS terminal is located directly on top of the maximum-height obstacle.
- The MSS terminal is turned on and operating in its satcom (as opposed to its cellular) mode.
- The MSS terminal is radiating at maximum EIRP. This occurs, even though there are no obstructions above the MSS terminal that would cause it to switch to high-power mode.
- The MSS terminal maximum EIRP out-of-band emissions are at the maximum value of the specified emissions mask.
- The MSS terminal is assigned its worst frequency from an interference perspective.
- The GNSS receiver barely satisfies the minimum design requirements for RFI robustness (normal receiver production margins or anticipated improvements are not considered).

The conservative analysis in Section 6 of this Appendix demonstrates that the probability of loss of navigation caused by MSS interference is negligible compared to the RNP standard. The probability for an MSS alarm (indicating loss of navigation service) is less than 10^{-13}, or one ten millionth of the value of the RNP standard. This is equivalent to one missed approach in 10,000 billion attempts!

The concern of the aviation community regarding MSS interference is clearly not a safety issue, by any reasonable assessment of risk. The only way the aviation community can claim a concern is to arbitrarily disallow the use of standard probability methods for risk assessment (which they have suggested).

The MSS unwanted emissions at the levels specified in the MSS emission mask pose no threat to the use of GLONASS in any phase of flight, including Cat I precision approach.

Other Sources of Undesired Emissions

The MSS community believes that the aviation community would make a serious mistake if it adopted avionics susceptibility standards which require extremely low levels of interference for acceptable operation, such as the -70 dBW/MHz level they have proposed. Known and projected emissions from environmental sources and various electrical equipment are virtually certain to exist at levels exceeding the emission mask level the aviation community has proposed. Also, there are many other sources of mobile interference that have not been fully addressed, but which may be of serious concern if the extremely low susceptibility is employed.

For example, mobile amateur radio, VHF and UHF mobile radios, and satellite earth stations of the Global Maritime Distress and Safety System (GMDSS) can all generate emissions 10 to 20 dB above the mask level proposed by the aviation community. These systems are in operation today, are ubiquitous and are present in very large numbers.

The low emission mask has other problems as well, e.g., there are many cases of malfunctioning electrical equipment generating emissions capable of disrupting GNSS-based navigation equipment and other systems at close range. Even if the MSS community were able to reduce emissions further, GLONASS (and GPS/WAAS) would remain at possibly greater risk from these and other interfering sources.

Effects of the Low Level Interference Environment

Fundamental systems engineering principles and the overriding need to ensure flight safety dictate that the aviation community take seriously the multiple and pervasive low level interference possibilities and take steps to assure that aviation navigation systems operate acceptably in the actual interference environment.

The aviation community has focused heavily on the MSS emissions and has proposed extreme emission standards that, in their entirety, are unachievable by the MSS and other communities. As has been shown, MSS emissions do not impact safety and further, may be a minor concern in the overall interference perspective.

Receiver Considerations

In addition to the changes previously suggested, hybrid GPS/GLONASS/WAAS receivers can and should be designed to significantly reduce transient interference susceptibility and provide other improvements in performance by the incorporation of vector tracking loops (and other similar developments) or by the use of simple accelerometer aiding of the GNSS receiver to track through transient interference events, or by both. These improvements can eliminate harmful transient interference from all sources, not just MSS, without dependence on the use of other navigation equipment, such as inertial navigation systems.

GLONASS Band Emission Levels

The aviation community has proposed that MES emission levels in the GLONASS band (1597-1605 MHz) meet the emission levels which were earlier proposed for the GPS/WAAS band (-70 dBW/MHz). This proposal lacks consensus, is not based on a demonstrated need, and is not consistent with sound engineering practice, considering the proximity of the GLONASS band to the MSS band.

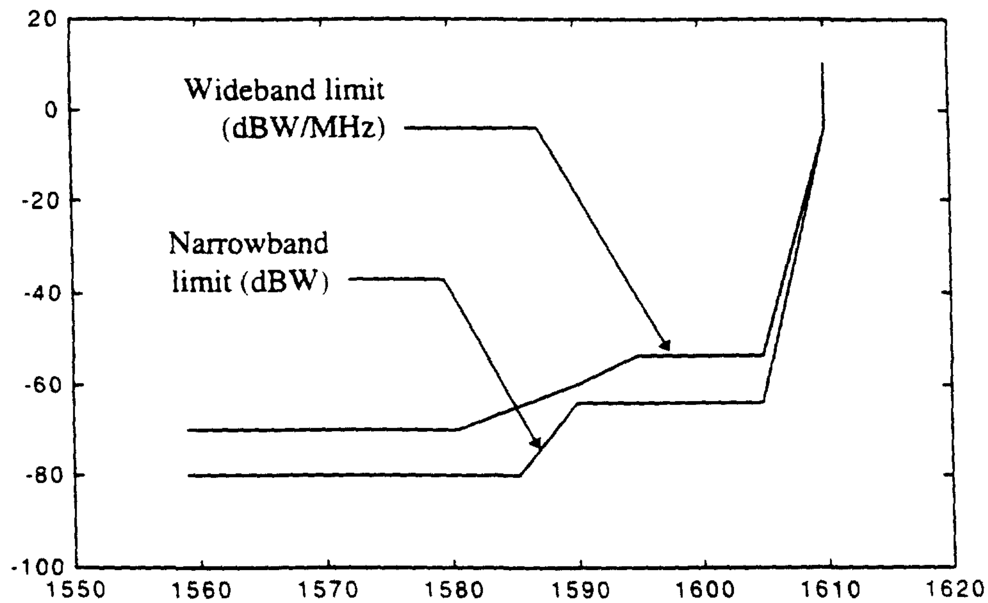
The MSS community agreed to the proposed emission level for the GPS/WAAS band because it is achievable (by the MSS community) considering the appreciable separation between the GPS and the MSS bands. At the time (and now) the MSS community recognized that the FAA proposed emission level is unnecessary.

Summary and Conclusions

The MSS community's proposed emission limits are safe and fully adequate to protect commercial quality, combined GPS/WAAS and GPS/WAAS/GLONASS navigation receivers for operations in all phases of flight, including Cat I precision approach. Figure E1-1 displays the MSS community's proposed MES EIRP emission limits.

The interference vulnerability of combined GPS, WAAS and GLONASS navigation receivers is substantially reduced (improved) when they are integrated using prudent engineering practice, taking advantage of current technology. An emission level of -54 dBW/MHz for the GLONASS band, as proposed by the MSS community, is more than adequate to protect GLONASS signals in a hybrid receiver.

Figure E1-1:
The MSS Community's Recommended MES EIRP Emission Limits.



The more stringent emission limits proposed by the aviation community are not necessary and have no relation to safety or to any improvement in performance. Although these stringent limits can be met by the MSS community in the GPS/WAAS band, they are not needed. These emission limits are not feasible or attainable in the GLONASS band because of the proximity of the GLONASS and MSS bands.

Severe economic penalties would be placed on the MSS community and other communities which use radiating (or non-radiating) electrical equipment if the U.S. aviation community's more stringent emission levels are imposed.

E.2. INTRODUCTION

In late 1993 the RTCA was requested to review the characteristics of GPS and GLONASS, identify potential sources of interference, and recommend mitigation methods for aviation sensors. This activity was assigned to Working Group 6 (WG6) of Special Committee 159 (SC-159). WG6 has had over 25 meetings (at roughly one month intervals since early 1994), with proactive MSS community involvement.

Among the many varieties and kinds of interference there is a type associated with transmissions from vehicular, portable, transportable or hand-held Mobile Satellite System (MSS) Mobile Earth Stations (MES). A Memorandum of Understanding between the FCC, NTIA and FAA requested that, under the auspices of the RTCA, the aviation and MSS parties attempt to reach a consensus on new MSS MES transmitter out-of-band emission standards for protection of Global Navigation Satellite Service (GNSS) receivers and on GPS/GLONASS receiver susceptibility standards.

Consensus has been achieved on out-of-band MSS MES emission control type of protection for GPS/WAAS. However, the protection of GLONASS, due to its spectral location close to the MSS band, requires additional consideration. Consensus has been elusive on methods for providing protection to the GLONASS portion of GNSS.

This Appendix summarizes the results of the Working Group 6 deliberations, the MSS participant's perspective in this matter and discusses the manner in which the MSS community believes compatible operation with aeronautical GNSS navigation can be achieved.

E.3. COMPARISON OF AVIATION AND MSS GLONASS LINK BUDGETS

E.3.1 Statement of the Issue

The aviation participants and the MSS participants agree on the mechanics of worst case link budget calculations but disagree on the values for the parameters in the budgets. This section provides a side by side comparison of the budget parameter values used by each party with explanations for the MSS values. Table E.3-1 contains the two link budgets for Category I approaches at the point in the approach when the aircraft is nominally at the threshold decision altitude (height) (DA(H)) – the point of closest possible approach to a mobile terminal while the navigation equipment is being used as the primary source of guidance.

The MSS participants contend that manufacturers, implementors and operators of GNSS equipment for aviation can take measures of relatively low cost and risk that will provide additional interference mitigation relative to their stated position. These measures, coupled with the achievable MSS EIRP broad-band emission limit of -54 dBW/MHz, result in positive margin for Category I approaches in a worst-case link budget. In fact, it is shown in Section 5 of this Appendix that the probability of having any effect at all on the navigation output of a well designed GLONASS sensor and antenna is totally negligible.

Table E.3-1: Category I Link Budget Comparison (200' threshold DA(H))

Parameter	Units	Aviation Budget	MSS Budget
Reference Carrier Power (min)	dBW	-161	-160.5
GLONASS Antenna Gain (min)	dBic	-4.5	-2.0
Correlator Losses (max)	dB	-2.5	-1.6
Received Carrier Power	dBW	-168	-164.1
Thermal Noise Density (max)	dBW/Hz	-201.6	-203.1
C/No	dB-Hz	33.6	39.0
Threshold C/(No+Io)	dB-Hz	30	28.5
Threshold C/Io	dB-Hz	32.5	28.9
Threshold Received Io	dBW/Hz	-200.5	-193
MSS EIRP Density (max)	dBW/MHz	-70	-54
Bandwidth conversion	dBHz/MHz	-60	-60
Separation Distance	feet	100	150
Path Loss	dB	-66.1	-69.6
Antenna Gain Toward MSS	dBic	-10	-12
Received Interference Density	dBW/Hz	-206.1	-195.6
Margin Relative to Threshold Io	dB	5.6	2.6

E.3.2 Carrier Reference Power

The aviation participants state that the worst case reference power quoted in the GLONASS Interface Control Document should be used in the calculations. The reference power is -161 dBW into a +3 dBi linearly polarized antenna, occurring at a 5 degree mask angle. The corresponding power into a circularly polarized 0 dBic reference antenna is -161 dBW.

The MSS participants contend that the worst case reference power should be taken from the GLONASS ICD at a mask angle of 15 degrees (see the discussion of mask angle considerations in Section 3.3 below). The corresponding carrier reference power is -160.5 dBW. The actual carrier reference power will typically be 1-2 dB higher than this level, since GLONASS spacecraft rarely operate exactly at their minimum specified value. Since interference is a rare event and since RNP is characterized in probabilistic terms, it would be more appropriate to consider a range of carrier reference power levels with the minimum specification as the lower bound; however, this analysis will accept the ICD value and will consider any additional power as a form of "hidden margin" that provides additional robustness to the navigation system as a whole.

E.3.3 GLONASS- Directed Antenna Gain

The aviation participants have selected a 5 degree mask angle as being necessary to assure that sufficient GLONASS satellites are in view to meet availability and integrity requirements during precision approaches. The corresponding minimum antenna gain toward a GLONASS satellite at 5 degree mask angle is -4.5 dBic. The 5 degree mask was selected for "parity" with GPS, which in turn selected 5 degrees to ensure needed levels of availability, continuity and integrity given a constellation of 24 satellites.

Because GLONASS will be used to augment GPS/WAAS in the U.S., the MSS participants contend that a 15 degree mask angle for GLONASS is more than adequate to meet availability and integrity requirements for precision approaches. WAAS will provide the primary source of integrity monitoring for both the GPS and GLONASS constellations. A study by a GNSS receiver manufacturer has shown that at least 11 GNSS satellites are always visible when the GLONASS mask angle is 15 degrees and the GPS mask angle is 5 degrees. There are more than enough satellites to insure that the availability, accuracy and integrity requirements are met. This conclusion is based on additional studies of a hybrid GPS/GLONASS constellation summarized in Table E.3-2 below. A reasonable worst-case scenario was constructed by removing three satellites in each of the GPS and GLONASS constellations, such that all six removed (i.e., failed) satellites are above the horizon, and in the same sector of the sky, as viewed from the central portion of the United States. In this reasonable worst-case scenario, VDOP averaged 1.86 and never exceeded 5.33. The number of satellites in view, Nsat, averaged 12 and never dropped below 7. This compares favorably with GPS alone, under the condition of three satellites failed. In fact, the performance of the degraded GPS/GLONASS constellation with a hybrid mask was comparable to a completely healthy GPS constellation. When two WAAS satellites were added (the minimum required to support precision approach), the results were similar with GPS/GLONASS/WAAS and a hybrid mask out-performing GPS/WAAS alone (with three GPS satellite failures), and showing comparable performance to a fully-healthy GPS/WAAS constellation. (NOTE: maximum VDOP favored a fully-healthy GPS/WAAS constellation, but average and minimum number of satellites in view favored GPS/GLONASS/WAAS with a hybrid mask). Since the FAA will eventually certify public-use precision approaches with a GPS/WAAS constellation, accepting occasional but inevitable GPS satellite outages, it is clear that a GPS/GLONASS/WAAS constellation with a hybrid mask will satisfy operational requirements, ensure safety of flight, and perhaps even offer an availability improvement.

Table E.3-2: GNSS Performance Data for Hybrid Constellations

Number of S/C (Total)	Number of S/C by type, and Minimum User Elevation Mask Angle (N/Mask)			VDOP		Number of Visible Satellites	
	GEO	GPS	GLONASS	mean	max	mean	min
24	-	24/5.0	-	1.92	3.09	7.5	6
21	-	21/5.0	-	3.16	100.	6.7	4
26	2/5.0	24/5.0	-	1.85	3.06	9.6	7
23	2/5.0	21/5.0	-	2.01	42.62	8.7	5
42	-	21/5.0	21/15.0	1.86	5.33	12.0	7
42**	-	21/15.0	21/15.0	2.36	9.68	10.6	7
44	2/5.0	21/5.0	21/15.0	1.82	4.21	14.0	9

Table E.3-2 actually **overstates** the performance of GNSS architectures with 5 degree mask angles applied to precision approach (e.g., the row entries associated with GEO overlays). This is due to the fact that pseudo-range accuracy for low-elevation satellites is degraded by reduced signal strength, increased ionospheric and tropospheric error, and increased levels of multipath. As a result, **GNSS sensors certified for precision approach will apply a de-weighting algorithm during the satellite selection process, which will tend to reject low-elevation satellites and favor high-elevation satellites.** The quantitative effect of this process will depend on the number of tracking channels in the receiver and possibly other parameters, and has not been evaluated by any researcher to date. Nevertheless, it is clear on a qualitative basis that this process will tend to de-emphasize any benefits of low-elevation satellites.[5] In the context of a hybrid constellation, it is possible that satellites below a 15 degree mask angle would never be selected, even if the mask angle were 0 degrees! In fact, simulation data indicate that **it is probably feasible to increase GPS mask angles to 15 degrees as well, in the context of a hybrid constellation, and still meet RNP requirements.** An adjustment to the mask angle, from 5 degrees to 15 degrees, would also minimize the probability of a signal drop-out during the final phase of a precision approach due to blockage by a wing, tail surface, or surrounding terrain.

Based on this analysis, the MSS community recommends an elevation mask angle for GLONASS satellites of 15 degrees (and suggests that the aviation community consider a similar mask angle for GPS satellites, in the context of a hybrid constellation and a hybrid receiver). The minimum antenna gain in the RTCA/DO-228 MOPS toward a GNSS satellite at 15 degrees mask angle is -2 dBic. As with carrier reference power, directive antenna gain will actually exhibit a range of values. However, this analysis will assume the minimum-specified value and consider any additional gain toward the desired signal as a form of "hidden margin" that provides additional robustness to the navigation system as a whole.

E.3.4 Correlator Losses

The aviation participants claim that the correlator losses can be as high as 2.5 dB. Correlator losses include losses due to imperfections in the transmitted waveform, mismatch between the incoming waveform and the receiver reference waveform and A/D converter quantization losses.

There will be some losses incurred in the decorrelation process. The GLONASS ICD states that the transmitted waveform loss can be as great as 0.6 dB. QUALCOMM, a recognized world leader in CDMA technology, has demonstrated that a high quality correlator should have no more than 0.5 dB reference mismatch loss. As for the A/D quantization loss, the use of a multi-bit quantizer (instead of a minimum performance 1-bit quantizer used in many low-cost, consumer-grade GPS receivers) should introduce no more than an 0.5 dB loss. Therefore, the total loss of a commercial-quality receiver should be less than 1.6 dB.

E.3.5 Thermal Noise Temperature

The aviation participants assume a system noise temperature of 500 K equivalent to a system noise figure of 4.4 dB and a noise power density of -201.6 dBW/Hz.

A commercial-quality antenna and receiver at these frequencies can be designed to have a system noise temperature of less than 350 K (Noise Figure < 3.4 dB), or a noise power density of -203.1 dBW/Hz. Such system temperatures have been achieved at low cost in high production volume MSS terminals with omni-type antennas and are clearly achievable in quality GNSS sensors both today and in the future. Currently available GPS avionics from some manufacturers have receivers with noise temperatures less than 250 K.

[5] Low-elevation GLONASS satellites will tend to be de-emphasized more than low-elevation GPS satellites due to the higher susceptibility of GLONASS signals to multipath.

E.3.6 Threshold C/(No+Io)

The effective threshold of the receiver is specified in terms of the sum of the thermal noise power density and the interference power density. This threshold is determined by the most sensitive parameter that might affect the navigation output of the receiver.

The aviation participants assume that the interference behaves like thermal noise of equal power density and that the interference duration is long enough to disturb the accuracy of the pseudo-range output of the GLONASS portion of the GNSS receiver. The required C/(No+Io) under these conditions is claimed to be at least 30 dB-Hz.

There is agreement that wideband interference behaves like thermal noise of the same power density. However, the interference is definitely not present long enough to be considered steady state. The total duration of a transient interference event has been shown to be less than 2 seconds for aircraft passing through the decision threshold at approach speeds. Moreover, the aircraft antenna coupling in the direction of a ground mobile emitter varies from minimum to maximum at a rapid rate as the antenna downward lobes (if any are present) pass over the emitter. Maximum coupling occurs for at most a fraction of a second. GNSS receivers use smoothing filters on code derived range with integration time constants of 20 or more seconds. Short transients have negligible effect on accuracy.

Precision approach GNSS receivers use carrier smoothed aiding to track changes in velocity and range that cannot be tracked by the code loop. Carrier phase is used for this purpose because it generates virtually no additional noise into the output and is highly accurate in measuring changes in velocity and direction.

Interference transients may cause momentary carrier cycle slipping. Carrier cycle slips may cause phase jumps that appear as range jumps in the aided output. The receiver causes the effect of these jumps to decay relatively rapidly, typically by use of some form of exponential filtering. (A step function decays at an exponential rate).

Receivers are designed to detect the presence of range jumps and activate protective strategies. A detected jump may cause a continuity alert to occur if the receiver has not recovered within the alert time limit.

The CAT-I precision approach alert time limit for positioning (navigation) failure is 5 seconds[6].

The duration of mobile caused interference transients is less than 1 second. Should cycle slipping exceed the threshold during this time, there are 4 seconds for the receiver to recover before generating a continuity alert. *A well designed receiver should be able to recover in this time if the receiver does not loose carrier lock.* Even if it does occur on one carrier, the output from another tracked carrier not currently used in the range solution can be substituted. Hence the presence of cycle slipping does not imply that an alert will occur. If lock is lost, the carrier smoothing range ambiguity must be re-established before navigation aiding can be used.

The C/(No+Io) threshold value selected by the MSS proponents is 28.5 dB-Hz at a probability of cycle slip rate of 1 in 10,000 per second. This value was taken from simulation results contained

[6] "Minimum Operational performance Standards for Global Positioning System/wide Area Augmentation System Airborne Equipment", (WAAS MOPS), RTCA Document No. RTCA/DO-229, January 16, 1996, Section 2.2.4.6, alerts.

in the Report Appendix D. Figure D-3. This value should assure that loss of lock is a highly unlikely event.

E.3.7 Threshold Io Results

Threshold Io values were derived by subtracting the thermal noise contribution from the total C/(No+Io) allowance. The aviation budget C/Io threshold value is 32.5 dB-Hz while the MSS value is 28.9 dB-Hz. The threshold Io levels are -200.5 and -193 dBW/K/Hz, respectively, a difference of 7.5 dB. This indicates that the actual Io threshold is 7.5 dB higher than the aviation link budget value.

E.3.8 MSS EIRP Density

The aviation participants claim that a MSS EIRP wideband interference density value that is the same as that agreed for the GPS band, -70 dBW/MHz, is required. This argument is based on the claim of similarity of GLONASS and WAAS/GPS receiver operations, prior agreement of -70 dBW/MHz in the 4 MHz band centered on GPS L1 (which the MSS community never considered necessary), and the aviation-proposed link budget.

The aviation budget assumes that WAAS is the limiting factor and that the same conditions apply to GLONASS receivers. This is simply not the case. WAAS is more susceptible to steady state noise and interference than either GPS or GLONASS. Therefore using WAAS criteria for GLONASS is not valid.

The MSS participants have concluded that a value of -54 dBW/MHz is the best that can be achieved under maximum EIRP conditions at 1605 MHz given the available technology suitable for use in hand-held MSS radios. (See section 4.0 for details). Handsets will be tested to this level during production. Actual handsets will perform at least 4 dB lower than this threshold, even at peak power and when tuned to the lowest operational frequency in the MSS band. As with carrier reference power and directive antenna gain, this difference will be considered as a form of "hidden margin" that provides additional robustness to the navigation system as a whole.

E.3.9 Threshold DA(H) and Separation Distance

Category I approaches have a minimum threshold DA(H) of 200 feet measured relative to the runway surface. As an aircraft approaches the decision point (when a pilot will visually acquire the runway and stop relying on instruments for guidance), it is allowed to be above or below this height due to navigation sensor error and flight technical error. In addition, the FAA rules specify a minimum obstacle clearance surface (OCS) which implicitly defines a point 77 feet above the touchdown point, as measured at the point on an approach when an aircraft on a 3 degree glide slope would nominally be at an altitude (above touchdown) of 200 feet. This is intended to provide separation relative to physical obstacles that could contribute to an accident.

The aviation participants claim that the minimum separation distance between an aircraft and a mobile terminal can be as little as 100 feet. This distance was derived by assuming the aircraft is at the lowest point in its 95% containment tunnel, and that an MSS emitter is at the highest altitude allowable by the OCS directly under the Decision Point associated with a 200 foot DA(H). Essentially, the aviation participants have explicitly equated the OCS with possible locations of MSS emitters. The MSS community disagrees with this analytic assumption. The OCS was defined to protect an aircraft from physical collision with an obstacle that could cause loss of control and an accident -- these obstacles are typically but not always such things as trees, chimneys, poles, cranes, etc. When defining a precision approach, the FAA examines such objects in and near the approach corridor to ensure they are not a threat. The first iteration of this analysis uses the OCS. If a potential problem is identified, the FAA considers adjustments to the approach procedure such as a movement in the touchdown point, an increase in the glide slope, an increase in the DA(H), an offset in the approach azimuth, etc. In rare cases, a precision approach may not be allowed because of these obstacle considerations. **The key point is this: the OCS is an analytic tool, which was defined to assist the FAA in estimating collision risk on final approach relative to physical obstacles -- it is inappropriate to equate this surface with possible locations of MSS emitters.** MSS emitters will be located on the ground, either using hand-held or vehicle-mounted equipment. In rare instances, they might be on a building rooftop or multi-story garage. These cases should certainly be considered in the determination of a national policy for MSS emissions control and GNSS operations, but are the exception rather than the rule. As with the existing procedures for physical obstacles, exceptional cases should be handled on an exceptional basis, rather than as the norm (note: MSS users on rooftops or the tops of multi-story garages would almost certainly have clear line-of-sight to a terrestrial cellular site, and would operate in a terrestrial mode).

The MSS community has examined the terrain profiles of 57 airports comprised of the 50 busiest airports in the U.S., as well as all civilian airports in the lower 48 states scheduled to receive a Category I MLS installation. This examination indicated that the majority have depressed or level terrain, not elevated terrain. Elevated roadways and buildings are rare. Of the 330 runway ends examined, only 7 were associated with terrain near the decision point higher than 30 feet above the touchdown point (about 2%). The conclusion is that most CAT-I approaches will have separation distances on the order of 150 feet, versus the 100 feet proposed by aviation. In those cases where the separation distance might be less to where a mobile ground emitter might reasonably be located, there are several operational options (note that none of these have any bearing on GPS/WAAS approach procedures, which rely on signals at 1575.42 MHz).

1. Adjust DA(H) slightly (for hybrid GNSS equipment);
2. Adjust glide slope slightly (for hybrid GNSS equipment);
3. Use another runway at the airport;
4. Accept a minor increase in the probability that continuity might be affected (the predicted level of continuity would still exceed the FAA's own requirements); or
5. Avoid defining a hybrid GNSS-based approach to this airport.

Note that these options are similar to those already employed by the FAA due to consideration of physical obstacles. From a technical standpoint, it is feasible to consider a new criterion for GNSS-based precision approaches that would evaluate terrain height to assess the risk of radio-frequency interference (i.e., this criterion would not be required for ILS and MLS approaches due to the different technologies involved). Radio-frequency interference is considered less hazardous than a physical obstacle, since in the case of RFI, a relatively long sequence of low-probability events could lead to a missed approach, whereas in the case of a physical obstacle, a relatively short sequence of low-probability events could lead to a collision and consequent loss of life. Nevertheless, the FAA may choose to treat the two risks in a parallel paradigm.

From an economic standpoint, a new criterion for GNSS-based precision approaches would involve a small economic burden for the FAA (since it must consider this new factor), and a small (probably insignificant) economic penalty to civil aviation due to the marginal impact of procedure adjustments at the rare airports where terrain height may be a factor. The FAA currently builds about 500 approach procedures per year, and will be focused primarily on

GPS/WAAS approaches through the early part of the next century. It will be many years before any significant fraction of the runway ends in the United States will be equipped with GPS/WAAS precision approach procedures, and even longer before any significant fraction of runway ends are equipped with GPS/GLONASS/WAAS precision approach procedures. The economic penalties to civil aviation must be balanced against the economic penalties faced by the MSS community, due to burdensome requirements that are unjustified by physics and a broad view toward public policy.

E.3.10 Antenna Gain Toward an MSS Emitter

All of the available data from U.S. sources, including actual flight test data developed jointly by the U.S. Navy and the FAA (see Annex 2 and the associated summary in Section E.5 of this Appendix) support the conclusion that the downward gain is less than -12 dBic for all elevation angles below -30 degrees, and is less than -15 dBic for angles below -60 degrees. The data also shows a fine grained lobe structure below the aircraft that would cause the coupling to be less than the peak values over most of the downward volume of space, supporting the conclusion that peak interference transients, if present, will be of sub-second duration. The link budget value of -12 dBic is conservative for the angles associated with the minimum separation distance (i.e., at deflection angles lower than -60 degrees) and should be consistently achievable with well designed GNSS top-mounted antennas. The additional isolation apparent in the available data, both in terms of the antenna gain envelop function (to a level of -15 dBic) as well as the difference between the fine-grained structure and the envelop, appears justified based on analysis and testing, but may be difficult to certify. It will be considered as a form of "hidden margin" that provides additional robustness to the navigation system as a whole.

E.3.11 Interference Density Results

The aviation link budget shows that the received interference power density is -206.1 dBW/Hz while the MSS link budget shows the received interference power density to be -195.6 dBW/Hz, a difference of 10.5 dB.

E.3.12 Margin Results

The aviation link budget has a margin of 5.6 dB against interference, although there is only 3.6 dB margin against thermal noise -- a relatively small value for a safety-of-life system.

The MSS link budget has an interference margin of 2.6 dB, and over 10 dB against thermal noise, without consideration of the various forms of "hidden margin" noted above. Thus commercial-quality combined GPS/WAAS/GLONASS aviation navigation receivers are fully protected, with margin, from MSS emission levels that are practically achievable by the MSS participants. The two link budgets achieve the same degree of margin, but rely on different assumptions. Those of the MSS link budget are technically and economically achievable by both communities, with low risk, while those of the aviation link budget are technically and economically unachievable by MSS systems.

Not shown in this link budget is the performance of the WAAS signal, which is currently under review but may have margin as little as 1 dB. This is a consequence of the extreme assumptions adopted by the aviation community in their own analyses. It is not clear how one would certify such a system for precision approach, given its marginal performance in even a benign environment. One of the reasons for lack of progress in a compromise protection strategy may be the relatively fragile nature of GNSS-based navigation, when implemented with technologies baselined by the aviation community for purposes of this debate. There are more robust technologies, some of which have been noted in the main body of the report, which would improve overall tracking robustness and navigation system continuity. Adoption of these technologies would enhance performance in a benign environment, as well as environments characterized by radio-frequency interference from MSS and other sources.

E.3.13 Transient C/(No+Io) Versus Time

Figure E.3-3 plots example C/(No+Io) versus time for the aviation and MSS conditions. The aviation transient assumes the BAC1-11 scale model antenna data while the MSS transient assumes the measured data from a Sensor Systems GPS antenna measured in accordance with ARINC Characteristic 743A. Both transients last for less than a second and have similar shapes. It is important to note that the alarm time for a Category I precision approach is 6 seconds; thus, even if a transient occurred (a low probability event), which led to a loss of tracking on one or more GLONASS signals (another low probability event), which then led to a momentary loss of navigation in the sense that a full position and velocity solution could not be generated based on the data instantaneously available (a third low probability event), there would still be several seconds for the receiver to recover. It is within the power of the aviation community to develop equipment standards that would minimize the impact of such transients. Furthermore, **these plots assume that the downward gain characteristics of the installed GNSS antenna are fixed at the stated maximum gain**, and do not contain the fine-grained lobe structure exhibited by all available data. The difference between the actual fine-grained structure exhibited by real hardware, and the worst-case envelop assumed for analysis, can be considered as a form of "hidden margin" that provides additional robustness to the navigation system as a whole.

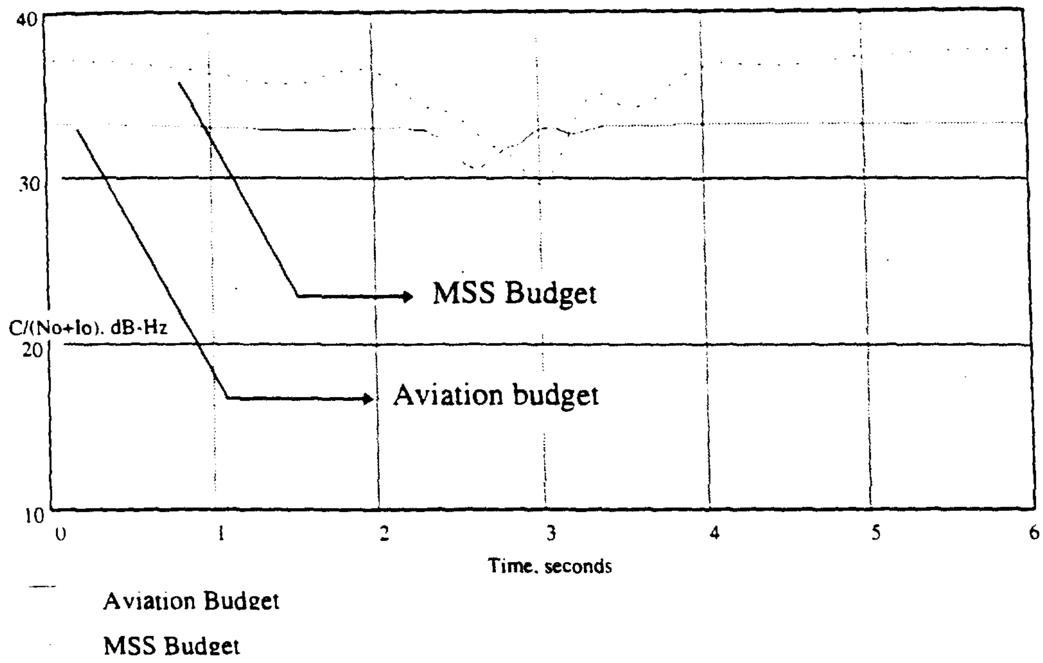
E.3.14 Other Mitigation Methods

The aviation participants have assumed a "minimum operational performance" GPS/WAAS receiver, whose interference susceptibility has been specified in RTCA/DO-229 so as to permit a wide latitude of hardware implementations. As noted above, this approach leads to relatively fragile performance in benign as well as RFI environments. There are methods of reducing receiver susceptibility to interference that are not included in existing specifications. Many of these are listed and described in the main report under the heading, "Mitigation Options for Significant Sources of RFI".

One of these implementation methods actually supported by FAA development funds, the vector loop tracking, is estimated to reduce interference susceptibility by 7 to 10 dB; values which provide substantial additional margin against all types of interference. At least one manufacturer of GNSS receivers indicates that this method could be implemented at relatively minor increase in receiver cost.

A second method, external aiding, can be used to assist carrier-aided tracking loops during interference transients. An example implementation is the incorporation of a relatively simple, inexpensive antenna mounted accelerometer. This device can measure short term changes in velocity and direction in a manner similar to carrier smoothing. Such a device would mitigate various kinds of transient interference, not just that from MSS terminals. Combining a vector tracking loop and an external aiding device could eliminate susceptibility to virtually all transients from most sources. This is particularly important for protection from interference due to inadvertent, unintended transmitters such as broken, mis-tuned or poorly-shielded electrical equipment.

Figure E.3-3: Transient C/(No+Io) Comparison



E.4. ACHIEVABLE MSS EIRP DENSITY LIMITS

E.4.1 MSS - GPS - GLONASS Spectrum Relationships

Table E.4-1 lists the MSS and GNSS bands and demonstrates the proximity of these bands one to another.

Table E.4-1: MSS and GNSS Frequency Bands

Band	Frequency Range, MHz
GPS L1	1573.42 - 1577.42
GLONASS L1	1597 - 1605
MSS LEO	1610 - 1626.5
MSS GEO	1626.5 - 1660.5

The GPS L1 band is centered on 1575.42 MHz with a main lobe bandwidth of ± 1 MHz[7].

The only GLONASS frequency plan considered by the WG6 is the planned "far-term" GLONASS L1 spectrum with CDMA channel centers between 1598.0625 MHz (channel -7) and 1604.25 MHz (channel +4). The GLONASS administration has indicated their intention to implement the frequency plan by the year 2005 (GLONASS Interface Control Document, provided at GNSSP/2). Testing in the United States has confirmed that relocation from the present GLONASS frequency band to the 1597-1605 MHz region will not be harmful to

[7] Narrow correlator receivers may operate over a wider bandwidth. However, noise outside the band 1575.42 ± 1 MHz is rejected by the $\sin^2(x)/x^2$ characteristic of the GNSS receiver's PN correlator.

GPS/WAAS. Only the narrow band GLONASS "C/A" code will be available for civil aviation navigation purposes. The wide band GLONASS "P" code is not subject to consideration or study since there is no plan to make it available to commercial aviation.

The MSS LEO band will be used by non-geosynchronous MSS systems operating with hand-held terminals. The lower portion of the band (1610 - 1621.35 MHz) has been initially allocated for use in the US by CDMA/FDMA systems while the upper portion of the band (1621.35 - 1626.5 MHz) has been allocated for use in the U.S. by TDMA/FDMA systems.

The MSS GEO band is used today by geosynchronous MSS systems operating with vehicle mounted and transportable/portable terminals. Currently, all MSS GEO systems operate using some form of narrow band FDMA.

E.4.2 Achievable Emission Limits For MSS Earth Stations

E.4.2.1 MSS Subscriber Unit Emission Sources

There are three types of MSS subscriber terminal emissions that may affect nearby bands. These types are (a) discrete spurious emissions due to synthesizer spurs, mixer products or harmonics of the transmitter, (b) wideband noise emissions due to the noise spectrum of the synthesizer and the noise figure of the transmitter chain, and (c) modulation side-lobe emissions due to the modulation method, the amount of pre/post filtering and the linearity of the transmitter. Figure E.4-1 is a general block diagram of the exciter stages and power amplifier stages of an MSS transmitter. A shaped/filtered data stream is used to modulate the local oscillator signal provided by the frequency synthesizer. This operation is done normally in a balanced modulator, to achieve a bi-phase suppressed carrier signal. The frequency synthesizer selects the carrier frequency over the tuning range. A wideband filter follows the mixer to attenuate out-of-band spurious and noise products. This signal is then amplified to the final power level and radiated by the antenna. Since size, weight, power consumption, heat generation, and cost are critical in terms of customer satisfaction, the overall design of the subscriber terminals must satisfy these constraints as well as the technical requirements of the MSS service, and coordination constraints associated with services in adjacent bands. Cavity or coaxial filters would be very large and bulky plus most likely prohibitive in cost even for vehicle-mounted units (where space and weight are less critical than for hand-held devices), and are completely unacceptable for hand-held units. Typically to meet the GLONASS criteria as shown above, a filter would have to achieve low insertion loss with good amplitude and phase performance in a 1% passband, while exhibiting an attenuation of 20 dB at 0.3% separation from the lowest transmitted center frequency.

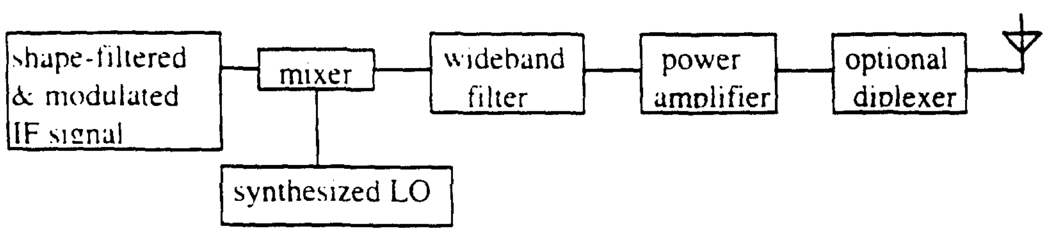


Figure E.4-1: General MSS Transmitter Block Diagram

The wideband filter must be wide enough to pass the tuned carrier while taking into account mass production variations, temperature induced shifts and passband gain flatness requirements. The materials used in the required miniature filters limit the Q, passband flatness, and out-of-band attenuation roll-off rate. Table E.4-2 lists the approximate required pass bandwidth (making an allowance of ±10 MHz for manufacturing and temperature variability and flatness), attenuation bandwidth[8], and the ratio of pass bandwidth to attenuation bandwidth relative to the GLONASS upper band edge. The MSS "LEO" band 1610 - 1626.5 is closer to the GNSS band than is the "GEO" band 1626.5 - 1660.5 MHz, but the "GEO" pass bandwidth is approximately double that of the "LEO" band.

The attenuation/passband ratio for LEO band transmitters is less than 1.0 -- a value that is not compatible with the available filters that meet the minimum requirements for MSS hand-held devices. It is not feasible to reduce either wideband noise, discrete spurs or modulation sidelobes using such a filter. Furthermore, there is a ripple effect on the design due to unwanted in-band attenuation provided by such filters, which drives up the power amplifier size and power, and increases the thermal load that must be dissipated and supported by the battery.

The ratio for the GEO band is about 1.43, a value that is marginal for more than a few dB of guaranteed attenuation using low cost, miniature ceramic filters, especially for low loss diplexers.

Table E.4-2: Bandwidth Ratios

MSS band 1610-1626.5	GLONASS @ 1605 MHz
Passband, MHz	16.5 + 20 = 36.5
Attenuation BW, MHz	27
Ratio atten/pass BW	less than 1
MSS band 1626.5 - 1660.5	
Passband, MHz	34 + 20 = 54
Attenuation BW, MHz	77
Ratio atten/pass BW	1.43

[8] The bandwidth outside of which signals are attenuated > X dB.

E.4.2.2 Wideband Noise Emissions

The IF modulator, the synthesizer, and any amplifiers in the chain generate wideband thermal noise that extends well beyond the tuning range of the device. Motorola's state-of-the art Iridium® SUBSCRIBER hand-held phone has a typical noise density of about -130 dBc, or a radiated noise density of -64 dBW at 1605 MHz. This is measured relative to a maximum EIRP of 6 dBW at 1621.5 MHz. This level of spectrum containment was achieved through data-shaping and the use of a Class AB power amplifier. In exchange for meeting this emissions level, Motorola sacrificed both battery life and unit cost. CDMA MSS systems, operating in the band 1610-1621.5 MHz, have greater difficulty minimizing emissions at 1605 MHz. Taking into account the 6 dBW maximum EIRP, and the demonstrated sidelobe isolation, the typical radiated maximum noise EIRP density is -54 dBW/MHz (at 1605 MHz).

Current GEO transmitters have carrier EIRPs ranging from about 3 dBW for omni-directional very low speed data terminals to as much as 36 dBW for INMARSAT-A terminals. AMSC's mobile telephone terminals, which have a maximum EIRP of 16.5 dBW, have measured wideband noise EIRPs of approximately -45 dBW/MHz within the passband of the filter. Typical measured EIRP density at 1605 MHz is about -63 dBW/MHz, showing the effect of the wideband filters on the noise level.

INMARSAT SDM (System Definition Manual) specifications for MESs are 21 dB higher than the proposed MSS out-of-band emission limits in the GLONASS band when integrated over a 1 MHz bandwidth. (INMARSAT C MESs are an exception, having a specified limit of -85 dBW/3kHz 1t 1605 MHz and -105 dBw/3kHz at 1575 MHz). However INMARSAT terminals tend to generate narrow-band spurious emissions which are more appropriately measured against a narrow-band specification. Absolute measured values of spurious levels for INMARSAT terminals are generally not available since tests for certification purposes are aimed to show that there are no spurious levels exceeding the required specifications rather than to measure the actual levels. Therefore typical certification testing results will show the noise floor of the measurement equipment rather than the actual spurious level. in a typical example (INMARSAT M) a measurement systems noise floor of -70 dBW/3kHz was measured at 1605 MHz, that is equivalent to -45 dBW/MHz. In another example (INMARSAT B) a measurement systems noise floor of -65 dBW/30kHz was measured near 1605 MHz, that is equivalent to -50 dBW/MHz. Typical measurements show a complete absence of MSS generated spurious emissions with respect to the measurement noise floor.

E.4.2.3 Discrete Emissions

The subscriber units of the AMSC GEO system measured discrete emissions at 1605 MHz less than -70 dBW. The manufacturers indicate that this level might be reduced further but at considerable expense. In an example measurement (INMARSAT-A) a discrete spurious level of -70 dBW was measured at 1605 MHz. However, such measurement results are rarely available from INMARSAT type approval testing. The LEO systems operators concluded that, while it might be feasible to limit discrete spurious emissions to approximately -80 dBW in the GLONASS band for vehicular units, it will be difficult if not impossible to limit hand-held subscriber unit emissions to less than -64 dBW.

E.4.2.4 Modulation Sidelobes

The GEO systems all use narrow-band modulation techniques as does the Iridium system in the LEO band. Modulation sidelobes for these systems do not extend into the GLONASS band. However, the CDMA LEO systems use wideband modulation of 1.25 Mbps or more. Because the separation between the upper GLONASS band edge of 1605 MHz and the lower MSS band edge of 1610 MHz is only 5 MHz, low level modulation side-bands may extend into the upper end of the GLONASS band. The CDMA LEO systems have concluded that the best currently available technology applicable to hand-held terminals limits EIRP in the GLONASS band to a value no lower than -54 dBW/MHz.

Modulation sidelobes are difficult to suppress. If filtering is provided prior to final stage up-conversion and amplification, the sidelobes can be reduced but tend to "re-grow" during amplification. If filtering is provided after up-conversion, but before amplification, the process is complicated by very demanding filter requirements (flat response over 16 MHz as well as many 10s of dB attenuation just 5 MHz away from the nominal channel center or 0.3% of the carrier frequency). Sidelobes will still tend to re-grow during amplification. If filtering is attempted **after** amplification, the problem is further complicated by the requirement for low filter insertion loss and high power handling capability by the filter. The available filters are not adequate to perform the function. Aggressive filtering in a hand-held terminal is unfeasible with current technology.

The most appropriate engineering approach is to rely on three techniques in combination, (1) pulse shaping to limit sidelobes and minimize sidelobe re-growth, (2) careful control of amplifier operating point, to avoid significantly nonlinear operations, and (3) general reliance on high-quality components to minimize noise and other non-linearity that could lead to spectral re-growth. Amplifier operating point (item 2) is particularly critical, and must be balanced against the need to maintain acceptable battery life and temperature. This three-pronged approach has already been adopted by all MSS licensees in an effort to ease coordination with GLONASS, and enable the use of hybrid GNSS equipment by civil aviation. This does not come for free -- significant but acceptable costs have been incurred.

The preceding worst case assumes that user peak power is held constant at maximum design levels. Sidelobes are reduced tremendously if peak power is reduced. In fact, **sidelobes will be reduced to very low levels in the vast majority of operational cases.** All LEO MSS systems rely on power control of user handsets in order to maximize system capacity and battery life. User terminals will only achieve maximum output power when there is no clear line-of-sight path to any satellite in view. Out-of-band MSS emissions on the order of -54 dBW/MHz at 1605 MHz would only occur under unusual conditions involving a terminal commanded to operate at maximum power on one of the lower MSS channels. The probability of this event, particularly for a user in close proximity to an aircraft on final approach, is exceedingly small. *It should be noted that at or near the end of most, if not all, runways, the line of sight to satellites at elevation angles greater than 10 degrees is unobstructed. Hence full power operations are highly unlikely.*

E.4.3 Technical Conclusions

Despite the wide variety of system architectures being developed, the MSS licensees were unanimous in their estimate of engineering capability associated with the MSS terminals themselves:

- **With respect to vehicle-mounted and transportable/portable terminals**, all MSS operators and licensees or their manufacturers stated that CW emissions could be limited to -80 dBW and wideband noise emissions could be limited to -70 dBW/MHz in the GPS L1 band[9]. It appears that limiting broad-band emissions to -70 dBW/MHz in the GLONASS band may be technically feasible for MSS operations in the GEO band and upper LEO band. **but severe size, power and cost penalties are expected to be necessary. Such values do not appear achievable for MSS vehicle mounted terminals operating in the lower LEO band (1610 - 1621.35 MHz).**

- The proposed unwanted emissions limit of -54 dBW/MHz at the GLONASS band could have a major impact on existing INMARSAT services providing distress and safety, as well as non-safety services, to a large number of MESs. However, INMARSAT agrees that the unwanted emission limits proposed by the MSS participants could be met, with acceptable economic penalty, by future MSS systems.

- **With respect to hand-held terminals**, all participating licensees stated that broad-band emissions in the GPS band (i.e., 1575.42 ± 2 MHz) could be limited to -70 dBW/MHz, and CW emissions could be limited to -80 dBW. **However, any attempt to limit emissions in the GLONASS band (1597 - 1605 MHz) to these levels will result in severe penalties in terms of terminal usability, terminal cost, and overall system capacity The MSS licensees have concluded that such levels are not feasible with currently available technology.** The attainable limits are -54 dBW/MHz for wideband noise and -64 dBW for discrete spurious emissions.

Table E4-3 lists the MSS proposed wideband MES EIRP emission limits while Table E4-4 lists the proposed narrow-band MES EIRP emission limits.

Table E4-3: MSS Proposed Wideband MES EIRP Emission Limits

Frequency Range (MHz)	EIRP Density (dBW/MHz)
1559 - 1580.42	-70
1580.42 - 1590.42	-70 linearly increasing to -60
1590.42-1595.42	-60 linearly increasing to -54
1595.42 - 1605	-54
1605 - 1610	-54 linearly increasing to -4
>1610	10

[9] Inmarsat can do so for terminals that are brought into service after 1998.

Table E4-4: MSS Proposed Narrow-band MES EIRP Emission Limits

Frequency Range (MHz)	EIRP (dBW) Note 1
1559 - 1585.42	-80
1585.42 - 1590.42	-80 linearly increasing to -64
1590.42 - 1605	-64
1605 - 1610	-64 linearly increasing to -4
>1610	10

Note 1. Measured in 700 Hz or less.

E.5. SUMMARY OF AVAILABLE GPS AIRCRAFT ANTENNA GAIN DATA

There is no specification that defines the gain of a GPS antenna below the horizon of a civilian aircraft.

During the course of WG-6 deliberations, substantial data was collected on antenna performance from various sources. The parties could not agree on the interpretation of the data so the aviation participants decided that the data should not be a part of the Final Report. Annex 2 presents that data because the MSS community believes it to be important to an understanding of a critical piece of any analysis.

Annex 2 includes information on the gain performance of GPS antennas below the aircraft horizon. This data includes results of testing the antennas relative to:

- a 1/9 scale aircraft model
- a static full-scale, 24 foot section of a Boeing 727 fuselage;
- in-flight measurements of GA aircraft owned and operated by the FAA and Transport Canada Aviation (TCA).

In their analyses, the aviation participants have chosen to ignore the full-scale testing, including the results of tests conducted and performed by aviation interests, such as the FAA, TCA and the U.S. Navy. Instead, the aviation participants have relied largely on the results of the 1/9 scale model testing, even though it has deficiencies, i.e.:

- The data is internally inconsistent;
- There is no useful documentation to help evaluate the modeling of the test antenna or the conduct of the testing;
- The tests were performed as part of a U.K. study to "demonstrate" that GPS could not be used in precision approach navigation.

The MSS interests, on the other hand, believe the full-scale testing of GPS antenna performance is far more representative of what can be expected in the real world, especially the in-flight evaluations performed by the Naval Air Weapon Center under the sponsorship of the FAA, TCA and GPS SPO. The details of these test results can be reviewed in Annex 2. In summary, the results of in-flight tests, static testing on a large section of fuselage and theoretical analysis support a conclusion that there is a minimum of 8 to 11 dB gain differential in GPS antennas between the gain at +5 and +15 degree elevation angles, and peak lobes 30 to 60 degrees below the aircraft horizon, and that differential gains will be greater at 60 to 90 degrees below the airccraft horizon.